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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF AIR-COOLED TURBINE BLADES IN TURBOJET ENGINE

IX - EVALUATION OF THE DURABILITY OF NONCRITICAL ROTOR BLADES IN ENGINE OPERATION

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EXPERIMENTAL INVESTIGATION OF AIR-COOLED TURBINE BLADES IN TURBOJET ENGINE

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SUMMARY

An investigation is being conducted to evaluate the durability of promising blade configurations of air-cooled rotor blades in a modified turbojet engine and to obtain some insight regarding the effect of vibration, large chordwise temperature gradients, creep, oxidation, heat-treatment, and method of fabrication on the life and the durability of blade configurations made of noncritical materials. The results obtained with 12 blades fabricated from noncritical materials are presented. These blades comprised five basically different structural or cooling configurations or both. Two of the configurations were modified at the leading and trailing edges to provide film cooling of the blades and thus decrease the chordwise temperature gradients at the possible expense of strength. Three of the configurations had no leading- or trailing-edge modifications and consequently had large chordwise temperature gradients.

The investigation of these blade configurations consisted in operating the blades over a range of continuous engine speeds from 4000 to 11,500 rpm and cooling-air flows per blade from 15 to 5 percent of the combustion-gas flow per blade. The blades which could withstand the continuous speed operation were subjected to a more severe test that consisted of alternate cycles of 5 minutes at idle speed (4000 rpm) and 15 minutes at rated engine speed (11,500 rpm) with 15 seconds allowed for acceleration or deceleration. At rated engine speed the effective gas temperature was maintained at 1450° F. This temperature corresponds to a turbine-inlet temperature of approximately 1670° F. The cooling-air flow per blade for the cyclic test was maintained at a constant value of 5 percent of the combustion-gas flow per blade at rated engine speed.

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The results of the investigation indicated that the blade configurations modified for film cooling were structurally unsatisfactory. Cracks developed across the leading edges of these blades after less than 1 hour of operation at rated engine speed because of vibration and the high stress concentrations.

The results with the blade configurations that had no modifications of the leading or trailing edges, however, showed promise of sustained engine operation. A blade of this type made of Timken 17-22A(S) alloy steel completed 200 cycles of operation (50 hr at rated speed), which was considered sufficient to demonstrate the durability of this type of blade from a structural and cooling standpoint. At the completion of the investigation, the blade was still in good condition except for considerable oxidation at the leading and trailing edges. The endurance investigation on a SAE 4130 steel blade was terminated after 154 cycles (38.5 hr at rated speed) because of severe oxidation at the leading and trailing edges. The investigation although limited in the number of blades tested indicates, nevertheless, that air-cooled rotor blades made of noncritical materials can be operated for extended periods of time at current turbine-inlet temperatures and engine speeds and can withstand repeated thermal shock. It was apparent, however, that some means, such as coatings, is required to inhibit oxidation of the blade shell.

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INTRODUCTION

An investigation of various configurations of air-cooled turbine blades installed in a commercial turbojet engine was started at the NACA Lewis laboratory in order to obtain a blade configuration that would permit engine operation at current turbine-inlet temperatures when noncritical blade materials were used. Materials that contain not more than 5 percent of critical alloying elements are considered as noncritical materials herein. The investigations of blades that had no special method for cooling the leading- or trailing-edge sections indicated that appreciable cooling of the midchord section was obtained (references 1 to 3). The leading- and trailing-edge portions of the blades, however, were considerably hotter than the midchord; consequently, large chordwise temperature gradients existed. With large temperature gradients, a redistribution of stresses would probably occur and the cooler midchord region would become the principal load-carrying section. Such a stress redistribution would probably permit satisfactory operation of this type of blade.

In an attempt to decrease the chordwise temperature gradients and to eliminate the necessity of stress redistribution, several methods of modifying the leading- or trailing-edge or both portions of the blades were also investigated (references 4 to 7). The investigations indicated that the chordwise temperature gradients could be reduced appreciably and that considerable cooling of the entire blade is possible. The blades modified in this manner appeared to be more desirable with respect to cooling effectiveness than those having high chordwise temperature gradients. When the leading- and trailing-edge temperatures are reduced through the use of slots or holes, the structural characteristics of the blade, however, may adversely affect blade life.

In order to investigate the problems of large chordwise temperature gradients, vibration, and the method of fabrication associated with the various configurations and also in order to investigate the problems of creep, oxidation, and heat-treatment associated with noncritical alloys, five blade configurations were subjected to a schedule of operating conditions in a production turbojet engine that was modified to accommodate several air-cooled blades.

In general, the investigation consisted of two types of test conditions. One type consisted in operating the blades over a range of constant engine speeds and the other type consisted of a cyclic-type test in which the engine was rapidly accelerated and decelerated in order to subject the blades to more severe operating conditions than the constant-speed running. A greater part of the research was at engine speeds of 11,500 rpm, a turbine-inlet temperature of 1670° F, and a ratio of cooling-air to combustion-gas flow per blade of 0.05.

APPARATUS

Engine

A production turbojet engine was modified to accommodate and to supply cooling air to several air-cooled blades. The modifications were the same as those described in reference 1 with the exception that one of the turbine rotors used in the investigation was modified to accommodate four air-cooled blades approximately 90° apart instead of the usual two, 180° apart, and the tail cone of the engine was further modified by decreasing the thickness of the shroud directly above the rotor blades from 1/8 to 1/16 inch. This was done so that the blades which failed would penetrate the thinner shroud and prevent damage to the remaining blades. In the investigation when the turbine-inlet temperature was held at a constant value, the temperature was controlled by an adjustable tail-pipe nozzle.

The cooling air for the air-cooled blades was supplied by a system external to the engine and was metered by flat-plate orifices. The cooling-air temperature at the inlet to the blade base was measured by chromel-alumel thermocouples.

In order to obtain the effective gas temperature, uncooled blades were instrumented with chromel-alumel thermocouples. The thermocouples were installed in the leading edge of the blade at a distance $2\frac{9}{16}$ inches from the tip. Two such blades were installed in the turbine rotor for each blade configuration investigated. 2392

A detailed description of the engine modifications and instrumentation is given in reference 1.

Cooled Blades

A total of 14 air-cooled blades were fabricated and investigated; 12 blades were made of cast or formed noncritical metals and two blades were cast from a high-temperature alloy. These blades comprised five different nontwisted blade configurations, hereinafter designated configurations A, B, C, D, and E. The blade materials used were SAE 4130 steel and Timken 17-22A(S) steel (noncritical materials) and a critical material, AMS 5382A. The chemical composition of these materials (references 8, 9, and 10, respectively) is summarized in table I.

Pertinent fabrication data for the blade configurations are summarized in table II.

<u>Configuration A</u>. - The first configuration (A) investigated had special film-cooled leading and trailing edges as shown in figure 1. The film cooling augmented the forced-convection cooling obtained with air-cooled blades such as those described in references 1 to 3. The leading edge was film cooled by passing air through three rows of radial slots (fig. 1). The leading-edge row consisted of four slots and the rows on either side of the leading edge had three slots each. These slots were 0.010 inch wide and about 7/8 inch long. Configuration A had a "sharp" leading edge, its radius being 0.05 inch. The trailing edge was film cooled by air passing through 29 holes of 0.040-inch diameter spaced 0.125 inch apart in a radial groove that was cut in the pressure surface of the blade 0.375 inch from the trailing edge. The tips of the blades were capped at the leading- and trailing-edge sections forcing a portion of the cooling air to flow through the slots and holes in the leading and trailing edges. The interior of the blade was packed with nine SAE 1020 steel tubes to increase the heat-transfer surface area in the midchord section. The tubes were Nicrobrazed in place. The leading-edge modification of configuration A was similar to that of blades 7 and 8 in reference 4, whereas the trailing-edge modification was similar to that of blade 6 in reference 4. Two blades (A1 and A2) of this configuration were cast of a noncritical material, SAE 4130 steel, and 2 blades (A3 and A4) were cast from a high temperature alloy, AMS 5382A. These blades were investigated as cast (no heat-treatment).

Configuration B. - Configuration B (fig. 2) was designed as a double flow blade in order to make use of natural-convection effects that would augment the forced convection and film cooling of configuration A. Configuration B was similar to blade 14 of reference 6, in which the cooling effectiveness of several double-flow blades is presented. The shells and bases of configuration B were integrally cast of SAE 4130 steel. Ten SAE 1020 steel tubes were Nicrobrazed in the midchord section of the blade so that they terminated approximately 1/4 inch from the tip of the blade, which was entirely capped (fig. 2).

The cooling air that entered the tubes at the base of the blade flowed radially outward into the space between the blade cap and the tube ends. The air then reversed direction and flowed radially inward in the leading- and trailing-edge regions of the blade. Part of the cooling air entering the base of the blade flowed directly into the leading- and trailing-edge regions. Thus the leading- and trailing-edge regions were cooled partly by the air that entered these regions after reversing flow direction upon flowing out of the tubes and partly by the air that entered these regions directly from the blade base.

The leading edge was film cooled by three rows of radial slots in the same manner as configuration A. The leading-edge temperature was further reduced by increasing the leading-edge radius from 0.05 inch (configuration A) to 0.099 inch (configuration B). Increasing the leading-edge radius decreases the heat-transfer coefficient at the leading-edge region as discussed in references 4 and 11.

Two radial slots that provided cooling-air-film coverage for the trailing edge were ground through the wall of the blade at the trailing edge. Each slot was 0.025 to 0.030 inch wide and about 1.5 inches long. Two blades (B1 and B2) of this configuration were investigated in the as-cast condition.

Configuration C. - The third configuration (C) investigated had the bases and shells integrally cast of SAE 4130 steel. This configuration (fig. 3) had nine steel tubes inserted and Nicrobrazed in the midchord region of the shell. No special method for cooling the leading- and trailing-edge regions was used. This configuration was similar to that reported in reference 1, in which the cooling effectiveness of this type of configuration is presented. Two blades (C1 and C2) of this configuration were fabricated and investigated in the as-cast condition.

Configuration D. - Configuration D was constructed by fillet welding formed shells of SAE 4130 steel to bases cast of the same material. After welding the shells to the bases, the blades were given a stress-relieving heat-treatment. The shell, which had an airfoil section similar to configuration C except for a relatively sharp leading edge having a radius of approximately 0.075 inch, was formed from a tapered tube into the blade profile. The details of this fabrication are presented in reference 12. No special method for cooling the leading- and trailing-edge section of this configuration was used.

The two blades (D1 and D2) of this configuration had nine steel tubes inserted into the formed shells. Blade D1 had the tubes Nicrobrazed in place and blade D2 had the tubes copper brazed in place. It is somewhat easier to fabricate blades with copper braze (reference 12), but blades having copper-brazed tubes had not been previously investigated for endurance, and it was not known whether this method of fabrication was suitable from an operational standpoint.

Configuration E. - Configuration E was fabricated from a formed shell having the same profile as configuration D. The formed shell was arc butt welded to a protruding lip on the cast base. (For details of this fabrication method, see reference 12.) This method was probably a more desirable method of attaching the shell to the base than the fillet weld employed in fabricating configuration D. Configuration E (fig. 4) had 12 steel tubes brazed in the midchord region. In all the previous configurations, the tubes terminated at the base of the shell as shown in figure 3 and the shell supported the entire weight of the tubes. In configuration E, however, the tubes were extended about 0.4 inch into the blade base and were brazed to the base. In this manner the tubes tend to support some of their own weight and thus the shell stresses are reduced (reference 1). A total of four blades (E1, E2, E3, and E4) of this configuration were fabricated. In order to investigate the endurance characteristics of another noncritical material and to compare the results with SAE 4130 steel, two of the blades (E3 and E4) were fabricated of Timken 17-22A(S) alloy and two (E1 and E2) of SAE 4130 steel. One blade of each of these materials had the tubes in the midchord section Nicrobrazed in place; two had the tubes copper brazed in place.

In order to increase the strength and to decrease the creep rate of this group of blades, both of the SAE 4130 steel blades (E1 and E2) and the Timken 17-22A(S) alloy blade (E4), which had the tubes Nicrobrazed in place, were heat-treated. The remaining Timken 17-22A(S) alloy blade (E3), which had the tubes copper brazed, was not heat-treated so that some comparison between heat-treated and nonheat-treated blades might be made. The heat-treatment consisted in heating the Nicrobrazed blades (E2 and E4) in a salt bath at 2000° F for 15 minutes and then isothermally quenching the blades in another salt bath at 1200° F for 15 minutes. The blades were then permitted to air cool to room temperature. This heat-treatment is considered one of the better heat-treatments for the materials used and is discussed in more detail in reference 12. The copper-brazed blade (E1) with an SAE 4130 steel shell was heat-treated in the same manner except the initial salt bath temperature was 1800° F and the isothermal quench temperature was 1000° F.

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Uncooled Blades

At the beginning of the endurance program, hollow, uncooled, nontwisted blades made of AMS 5382A alloy of the same profile as the cooled blades were placed adjacent to the cooled blade. This procedure was followed in order to decrease the unfavorable flow conditions that may arise by having the nontwisted cooled blade between the conventional twisted uncooled blades. Configurations A and B were investigated in this manner.

Before proceeding with the investigation of configurations C, D, and E, however, the uncooled nontwisted blades were replaced by the solid twisted uncooled blades that are conventionally used in the rotor of this engine. This replacement was necessary because of the repeated failure of the hollow uncooled blades. Thus, for the investigation of configurations C, D, and E, all of the rotor blades except the cooled blades under investigation were of the same configuration and material. From the data presented in reference 7, comparisons of the chordwise temperature distribution for an air-cooled blade having twisted and nontwisted blades adjacent to it can be made for engine speeds up to 10,000 rpm. The data indicate that with twisted or nontwisted blades adjacent to the cooled blade there is relatively small effect upon the chordwise temperatures on the cooled blade. Data are not presented in reference 7 for this comparison for engine speeds exceeding 10,000 rpm. Although the endurance tests were made at an engine speed of 11,500 rpm, the change in temperature distribution around the blade probably would still be relatively small and the endurance results would not be changed significantly.

PROCEDURE

Configurations A and B

The first configurations investigated were A and B, which had film-cooled leading- and trailing-edge sections. The investigation began with two blades of a configuration installed in the turbine.

Previous investigations of similar configurations showed that the cooling effectiveness of the leading-edge region decreased rapidly at low coolant flows (references 4 and 6). Consequently, in order to avoid operation of the blades of configurations A and B in a coolant flow range where decreased leading-edge cooling effectiveness is likely to occur, operation of these blades was made at high coolant flows. In order to provide somewhat of a cold spin test, initial operation of the blades was made at very high coolant flows (cooling-air to combustion-gas flow ratio per blade, 0.15) at engine speeds ranging from 4000 to 11,500 rpm. Periodic visual inspections of the blades were made, and if no failures occurred during the "cold-spin tests", the blades were then operated at reduced coolant flows (cooling-air to combustion-gas flow ratio per blade, 0.10) at engine speeds ranging from 8000 to 11,500 rpm.

The investigation of these blades was made with the adjustable tail-pipe nozzle in full-open position. The effective gas temperature varied from 937° to 1452° F (depending primarily on engine speed) during the course of the investigation. A summary of the engine operating conditions is shown in table III.

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Configurations C, D, and E

From the experience obtained during the investigations of configurations A and B, the operation of configurations C, D, and E at engine speeds below 10,000 rpm was dispensed with because the results obtained at lower engine speeds would have comparitively little significance.

Configuration C was operated over a range of cooling-air to combustion-gas flow ratios per blade from 0.15 to 0.05 at constant engine speeds ranging from 10,000 to 11,500 rpm. In addition to the constant speed tests, this configuration was subjected to a cyclic-type endurance operation. The cyclic tests consisted in operating the engine for 5 minutes at idling speed (4000 rpm) and accelerating the engine in 15 seconds to rated engine speed (11,500 rpm). At rated engine speed, the tail-pipe nozzle was adjusted to give an effective gas (or solid blade) temperature of 1450° F. This temperature corresponds to a turbine-inlet temperature of approximately 1670° F. These conditions were maintained for 15 minutes after which the engine was decelerated in 15 seconds to idling speed. This test procedure was repeated for each additional cycle. The cyclic type of operation was chosen so that the blades would be subjected to rapid changes in average temperature level, thereby exposing the blades to greater thermal shocks and making it necessary for a more rapid redistribution of stresses within the blades than are encountered in constant-speed running. Before the engine was started for the cyclic tests, the cooling air flow to the blades was set at a constant value that corresponded to 5 percent of the engine gas flow per blade at rated engine speed. The potentiality of operating air-cooled blades at lower cooling-air to combustion-gas flow ratios is indicated in reference 13; however, the value of 5 percent was arbitrarily chosen as the upper limit of the amount of cooling air that could be bled from the compressor without excessively reducing the over-all engine performance.

Configuration D was subjected only to the cyclic test. Configuration E, however, was subjected to both constant-speed running at engine speeds of 11,000 and 11,500 rpm and to the cyclic operation. All running was done at a cooling-air to combustion-gas flow ratio of 0.05 per blade.

The blades of these three configurations were visually inspected periodically for cracks or indication of impending failure. A summary of the pertinent engine operating conditions for these blade configurations is given in table IV.

RESULTS AND DISCUSSION

A summary of the endurance investigations of the five air-cooled blade configurations is presented in tables III and IV.

Blades Modified to Reduce Chordwise Temperature Gradients

The results of previous investigations (references 4 to 7) indicated that blades with special leading- and trailing-edge modifications had smaller chordwise temperature gradients than the unmodified blades and at the time showed the most promise of operation in present day turbojet engines; consequently, the first noncritical blades endurance tested were those having film-cooled leading- and trailing-edge sections.

Configurations A and B. - The endurance investigation of configurations A and B, which had the leading and trailing edges modified for film cooling, revealed a type of failure that was common to both configurations. After 3 to 6 hours of operation (see table III), three of the blades developed cracks between the radial slots in the leading-edge section. The cracks were perpendicular to the radial slots and developed in the same general area, approximately $1\frac{1}{32}$ to $1\frac{3}{8}$ inch from the blade base.

The cracks first appeared in blade A1 (cast of SAE 4130 steel with no heat-treatment). The cracks were welded and operation resumed. After 1 hour and 39 minutes of additional operation, one of the cracks reappeared and the blade was removed from the turbine. The investigation of configuration A was then continued with blade A2, which failed when the entire leading-edge section broke away from the blade shell. The total operating time for blade A2 was approximately 6 hours of which only 20 minutes were at rated engine speed.

The endurance investigation of configuration B, consisting of two SAE 4130 blades with no heat-treatment, is also summarized in table III. Cracks developed between the radial leading-edge slots of one of the blades after a total operating time of 3 hours and 24 minutes, of which 19 minutes were at rated engine speed. The investigation of configuration B was terminated at this point because of the repeated failures that had been experienced with blades having radial leading-edge slots.

In order to determine if the repeated failures at the leading edges were caused by the use of noncritical materials at elevated temperature or if the failures were caused primarily by vibratory stresses, two blades made of cast AMS 5382A, a high-temperature alloy, were investigated in the as-cast condition. These blades were the same as configuration A, except for the material. After operating the blade of AMS 5382A for a total of 2 hours and 45 minutes, of which approximately 1 hour was at rated engine speed, one of the blades developed a crack between the radial leading-edge slots; the location of the crack was similar to that on the blades made of SAE 4130 steel. Further investigation of the AMS 5382A blades was not made. It was observed that all the cracks in the leading-edge section of configurations A and B were located near the ends of the radial slots, where, because of the machining operation used in making the slots, a sharp edge existed, which probably resulted in high stress concentration at these points. It was thought, therefore, that some combination of vibratory stress and perhaps thermal stress, in addition to the high stress concentrations near the edges of the radial slots, caused the cracks.

In order to determine whether the cracks across the leading edge were caused by vibration fatique, an investigation of a blade similar to configuration A was made to determine which modes of vibration could have been responsible for the failures. The blade was mounted in a turbine apparatus as described in detail in reference 14. This investigation indicated that at certain modes of vibration the reeds formed by machining the cooling-air slots vibrated as separate beams producing high stresses in addition to the usual stress concentrations that exist at the end of the slots when the blade is rotating. It was also noted that most of the other modes had nodal lines that intersected the leading edge at or near the ends of these slots. Of the 15 modes that were recorded, seven had such intersections 3/8 inch from the blade base, and six had an intersection $1\frac{1}{2}$ inch from the base. These points apparently would be points of high vibratory stress. This is confirmed by the location of the cracks in the leading edges of the blades operated in the engine. Thus, it can be concluded that the failure at the leading edges of configurations A and B was caused essentially by the radial slots and not by the blade material used.

Although cooled blades with radial leading-edge slots of the type investigated appear to be structurally unsatisfactory as rotor blades at the present time, further research is required on other types of leading-edge modification that would eliminate the high stress concentrations at the edge of the slots and decrease the vibratory stresses at the leading-edge regions.

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Blades with Large Chordwise Temperature Gradients

Because of the repeated failures at the leading edge of film-cooled configurations A and B, noncritical blade configurations having no special leading- or trailing-edge cooling methods were investigated. Although blades of this type configuration have large chordwise temperature gradients, the redistribution of stress would probably occur and permit engine operation at current turbine-inlet temperatures. Consequently configurations C, D, and E were fabricated and investigated.

Configuration C. - One blade of configuration C (fig. 3) cast of SAE 4130 steel with no heat-treatment was installed in the turbine rotor for the endurance test. This blade was operated for 1 hour at both 11,000 and 11,500 rpm at a cooling-air to combustion-gas flow ratio per blade of 0.15. At the end of this time, the second and third tube inserts from the trailing edge, which were not completely in contact with the shell at the beginning of test, parted from the shell near the tip; nevertheless, the test was continued for a total time of 8 hours (4 hr at rated speed) when the second tube from the trailing edge broke approximately $1\frac{1}{4}$ inch from the base and damaged the tip of the blade as it came out of the cooling-air passage. An attempt to repair this blade was unsuccessful and it was removed from the rotor and replaced by a similar blade. Although a radiograph inspection of this second blade prior to installation revealed shrinkage and porosity above a third span length from the base, the blade was used in order to determine whether these defects had a serious effect on structural strength of the blade. After a total running time of approximately 31 hours (22 hr at rated speed) the test of this blade was terminated because of distortion and excessive creep at the trailing edge. The distortion of this blade after 2 minutes of the eighty-first cycle of operation as compared with a blade that had not been endurance tested is shown in figure 5. Small cracks at the leading edge, which are apparently hot tears, were also observed at the termination of the test. This excessive creep may have resulted because the blade was not heat-treated. Also the elongation may have been caused by malfunctioning of one of the engine components which occurred during the first 2 minutes of the eighty-first cycle and caused the effective gas temperature to reach a value of 1570° F, which is 120° F higher than that normally maintained for the endurance investigations. The engine was shut down immediately and the elongation of the turbine blades was observed.

For both blades of configuration C, a thin oxide scale had developed on the blade shells after 3 hours of operation. The oxidation did not progress to any observable extent after the thin oxide scale was first observed.

Configuration D. - In order to investigate the structural strength of blade configurations that would lend themselves to more rapid blade production than by integrally casting blades, configuration D was tested for endurance. The two blades of this configuration, D1 and D2, which were similar in profile and internal tube arrangement to configuration C had formed shells of SAE 4130 steel fillet welded to cast bases. Blade D1 had the tubes Nicrobrazed in place and blade D2 had the tubes copper brazed in place. Blade D1 failed at the base after 10 cycles and 9 minutes at rated engine speed because of insufficient weld penetration at the blade base. Further investigation of configuration D was terminated because the fillet weld method of attaching the shell to the base was apparently unsatisfactory.

Configuration E. - In view of the observed failure of configuration D, another method of welding that would give better weld penetration was attempted on configuration E by arc butt welding the shells to a protruding lip on the cast bases. As previously mentioned in this report, configuration E consisted of four formed blade shells, two of SAE 4130 steel and two of Timken 17-22A(S) alloy, which has higher strength properties than the SAE 4130 steel. Both of the SAE 4130 steel blades and one of the two blades made of Timken 17-22A(S) were heat-treated to increase further the strength and decrease the creep rate. The results of investigating the four blades of this configuration indicated that no significant creep was measured after the completion of 60 cycles of operation in addition to a total of 1 hour of constant-speed running at 11,000 and 11,500 rpm. No further measurements were made of the blade elongation because of the failure of an uncooled reference blade after 69 cycles, which damaged the tips of all the four cooled blades. Approximately 1/8 inch had to be ground from the tips of the blades to remove the damaged portions. The removal of this mass of metal from the tip decreased the centrifugal stress at the blade base by approximately 500 pounds per square inch. In the process of removing the cooled blades from the rotor for repair, the SAE 4130 steel blade with copper-brazed tubes (E1) was damaged at the leading edge to the extent that it was not considered satisfactory for further investigation. Therefore two of the 17-22A(S) blades were installed in another rotor and the endurance test was continued. After a total of 105 cycles of operation, the unheat-treated blade (E3) failed at the base. Inspection of the fracture indicated that the failure could possibly have been caused by a small structural defect that was known to have existed from the time the blade was fabricated. In place of this blade the remaining SAE 4130 steel blade (E2) was installed in the rotor and the cyclic running continued.

During the running of the 17-22A(S) and SAE 4130 blades a portion of the nozzle diaphragm failed and bent the tip of the 17-22A(S) blade E4 at the leading edge. The blade was repaired by grinding the leading edge at the blade tip. After a total running time of 154 cycles on the SAE 4130 blade and 190 cycles on the 17-22A(S) blade, inspection of the blades disclosed that the oxidation, which was first observed after 20 cycles of operation and which increased at the tip after 60 cycles of operation, was especially severe at the leading and trailing edges of the SAE 4130 blade E3 as shown in figure 6. This blade was removed from the rotor and replaced by a blade of similar configuration. The endurance test continued until 200 cycles were completed on the 17-22A(S) blade E4 at which time the test was terminated because the test conditions (50 hr at rated speed during the cyclic test) were considered sufficient to demonstrate the structural durability of these blades. A photograph of this blade after 200 cycles of operation is shown in figure 7. Because the tip at the leading edge was damaged by failure of an engine component, the tip was ground as previously mentioned. Considerable oxidation of this region is also apparent.

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The results of the endurance investigation, although limited in the number of blades investigated, show that air-cooled blades made of noncritical metals can be operated for extended periods of time in engines at current turbine-inlet temperatures; however, before these blades are considered completely satisfactory for gas-turbine application, some means such as coatings is required to inhibit the oxidation of the blades. It also appears that both the copper-braze and Nicrobraze methods of attaching the tube inserts to the blade shell are equally satisfactory, and the isothermal quench heat-treatment of blades made of noncritical materials decreased the creep rate and improved blade life.

SUMMARY OF RESULTS

The results of an experimental investigation to determine the durability of several air-cooled turbine-blade configurations made of noncritical materials are summarized as follows:

1. Air-cooled blades made of noncritical materials and having large chordwise temperature gradients are structurally satisfactory for sustained turbojet-engine operation at a turbine-inlet temperature of approximately 1670° F and a cooling-air to combustion-gas flow ratio per blade of 0.05.

2. Blades made of noncritical materials oxidized severely when subjected to the combustion gases for extended periods of time. It is evident that some oxidation resistant coating is necessary when low-alloy steels are used.

3. Several blades having radial slots in the leading edge for film cooling in order to reduce the chordwise temperature gradients were investigated and found to be structurally unsatisfactory because of inherent weakness in the designs.

4. The isothermal quench heat-treatment used on several of the blades made of noncritical materials apparently decreased the creep rate and increased blade life.

5. Attaching the blade shells to the blade bases by arc butt welding was preferable to fillet welding because of the insufficient weld penetration obtained with the fillet welds.

6. Both copper braze and Nicrobraze were apparently equally satisfactory from a structural standpoint for attaching the tube inserts to the blade shells.

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10. Anon.: Alloy Castings, Precision Investment, Corrosion and Heat Resistant. AMS 5382A, SAE, Sept. 1, 1948.

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12. Long, Roger A., and Esgar, Jack B.: Experimental Investigation of Air-Cooled Turbine Blades in Turbojet Engine. VII - Rotor-Blade Fabrication Procedures. NACA RM E51E23, 1951.

13. Schramm, Wilson B., Nachtigall, Alfred J., and Arne, Vernon L.: Preliminary Analysis of Effects of Air Cooling Turbine Blades on Turbojet-Engine Performance. NACA RM E50E22, 1950.

14. Kemp, R. H., Morgan, W. C., and Manson, S. S.: Advances in High-Temperature Strain Gages and Their Application to the Measurement of Vibratory Stresses in Hollow Turbine Blades During Engine Operation. Proc. Soc. Experimental Stress Analysis, vol. VIII, no. 2, 1951, pp. 209-228.

TABLE I - CHEMICAL COMPOSITION

Blade material	Chemical content (percent)										
	Carbon	Manganese	Phosphorus (max)	Sulfur (max)	Silicon	Chromium	Molybdenum	Nickel	Tungsten	Iron	Cobalt
SAE 4130	0.28 to .33	0.40 to .60	0.040	0.040	0.20 to .35	0.80 to 1.10	0.15 to .25	-----	----	Remainder	-------
Timken 17-22A(S)	0.28 to .33	0.45 to .65	0.040	0.040	0.55 to .75	1.0 to 1.5	0.40 to .60	-----	----	Remainder	-------
AMS 5382A	0.45 to .55	1.00 max	0.040	0.040	1.00 max	24.50 to 26.50	----	9.50 to 11.50	7.00 to 8.00	2.00 max	Remainder

TABLE II - BLADE FABRICATION DATA

Blade	Fabrication method	Shell material	Method of tube attachment	Heat-treatment
A1	Blade shell and base integrally cast	SAE 4130 Steel	Tubes Nicrobrazed and terminated at base of shell	None
A2		SAE 4130 Steel		
A3		AMS 5382A		
A4		AMS 5382A		
B1	Blade shell and base integrally cast	SAE 4130 Steel	Tubes Nicrobrazed and terminated at base of shell	None
B2		SAE 4130 Steel		
C1	Blade shell and base integrally cast	SAE 4130 Steel	Tubes Nicrobrazed and terminated at base of shell	None
C2		SAE 4130 Steel		
D1	Formed shell fillet welded to base	SAE 4130 Steel	Tubes Nicrobrazed and terminated at base of shell	Stress relieved after welding of shell to base
D2		SAE 4130 Steel	Tubes copper brazed and terminated at base of shell	
E1	Formed shell arc butt welded to base	SAE 4130 Steel	Tubes copper brazed and extending into base of blade	Isothermal quench
E2		SAE 4130 Steel	Tubes Nicrobrazed and extending into base of blade	
E3		Timken 17-22A(S) Steel	Tubes copper brazed and extending into base of blade	Stress relieved after welding of shell to base
E4		Timken 17-22A(S) Steel	Tubes Nicrobrazed and extending into base of blade	Isothermal quench

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TABLE III - SUMMARY OF ENDURANCE TESTS OF BLADES MODIFIED TO REDUCE CHORDWISE TEMPERATURE GRADIENTS

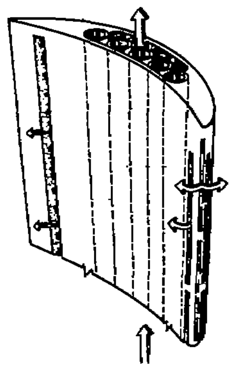
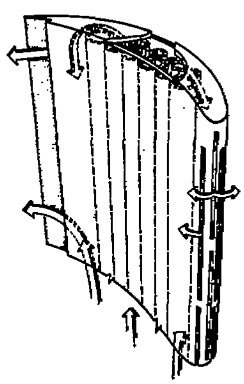
Blade configuration	Blade	Blade material	Nominal engine speed (rpm)	Time at speed (hr)	Time at speed (min)	Ratio of coolant to gas flow	Effective gas temperature (°F)	Remarks
 Configuration A	A1 and A2	Cast SAE 4130 steel	4,000		36	0.15	1007	Endurance test began with two cooled blades of same material.
			6,000		27	0.15	970	
			8,000		19	0.15	955	
			9,000		36	0.15	988	
			10,000		34	0.15	1070	
			11,000	1	0	0.15	1207	
			11,500		15	0.15	1352	Cracks developed perpendicular to vertical slots at leading edge of one cooled blade at $\frac{7}{32}$ inch, $1\frac{1}{32}$ inches, and $1\frac{3}{8}$ inches from base. Cracks welded, engine running continued.
			8,000		30	0.10	937	
			9,000		30	0.10	960	
			10,000		39	0.10	1058	Crack at $1\frac{1}{32}$ inches reappeared on blade A1. This blade removed from wheel and replaced with uncooled solid blade. Test continued with blade A2.
	A2		11,000		27	0.10	1270	
			11,500		5	0.10	——	Entire portion of leading edge comprised of radial slots broke away from blade shell. Test on blade terminated.
	A3 and A4	Cast AMS 5382A	4,000		25	0.15	1027	Endurance test began with two cooled blades of same material.
			8,000		20	0.15	1000	
			10,000		20	0.15	1057	
			11,500		15	0.15	1356	
			8,000		20	0.10	980	
			10,000		22	0.10	1094	
			11,500		43	0.10	1382	Crack perpendicular to vertical slots developed at leading edge of one cooled blade at $1\frac{3}{8}$ inches from base. Test on remaining blade not continued.
 Configuration B	B1 and B2	Cast SAE 4130 steel	4,000		35	0.15	976	Endurance test began with two cooled blades of same material.
			6,000		15	0.15	937	
			8,000		15	0.15	950	
			9,000		30	0.15	995	
			10,000		30	0.15	1118	
			11,000	1	0	0.15	1327	
			11,500		19	0.15	1452	Cracks developed perpendicular to vertical slots at leading edge of one of the blades at approximately $1\frac{1}{8}$ and $1\frac{5}{8}$ inches from base. Test on remaining blade not continued.

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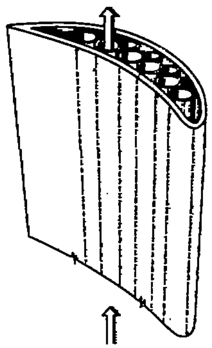
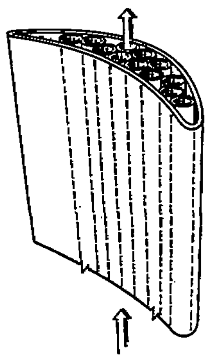
TABLE IV - SUMMARY OF ENDURANCE TESTS OF BLADES WITH LARGE CHORDWISE TEMPERATURE GRADIENTS

Blade configuration	Blade	Blade material	Nominal engine speed (rpm)	Time at speed (hr)	Time at speed (min)	Ratio of coolant to gas flow	Effective gas temperature (°F)	Remarks
 Configuration C	C1	Cast SAE 4130 steel	11,000	1	0	0.15	1224	Endurance test began with one cooled blade.
			11,500	1	0	0.15	1345	Two of the tubes, in shell of blade, nearest the trailing edge parted from the braze near tip of blade. Test continued with blade in this condition.
			11,000	1	0	0.10	1240	Thin oxide scale began to appear on the blade.
			11,500	1	0	0.10	1370	
			10,000	1	0	0.05	1095	
			11,000	1	0	0.05	1229	
			11,500	1	0	0.05	1338	
			11,500	1	0	0.05	1389	One of the tubes at trailing edge of the blade broke at $1\frac{1}{4}$ inches from the base and damaged blade tip. Attempt to repair blade was unsuccessful. Test on this blade terminated.
	C2		10,000	1	0	0.05	1063	This blade replaced the previous blade after it was removed from the rotor (X-ray inspection of blade prior to installation revealed porosity and shrinkage above third span length from the base).
			11,000	1	0	0.05	1237	
			11,500	1	0	0.05	1322	Thin oxide scale formed on blade.
			11,500	1	0	0.05	1450	
			4,000	6	40	——	——	Cyclic test (80 cycles completed). Engine shutdown after 2 min of the 81st cycle because of high turbine-inlet temperature due to malfunctioning of engine components. Inspection of the blade disclosed excessive creep at the trailing edge and hot tears at the leading edge. Test on the blade terminated.
			11,500	20	0	0.05	1450	
Similar to above blade Configuration D	D1 and D2	Formed SAE 4130 steel	4,000	1	0	——	——	Endurance test began with two cooled blades of same material. Cyclic test (10 cycles completed plus nine minutes of 11th cycle). Blade D1 failed due to insufficient weld penetration at the base. Test on blade D2 not continued.
			11,500	2	39	0.05	1450	
 Configuration E	E1	Formed SAE 4130 steel	11,000	—	30	0.05	1190	
			11,500	—	30	0.05	1515	
			4,000	5	45	——	——	Cyclic test. Oxide scale observed after 20 cycles. Blade completed 69 cycles. Blade damaged on removal from rotor. Test on this blade not continued.
			11,500	17	15	0.05	1450	
	E2		11,000	—	30	0.05	1190	
			11,500	—	30	0.05	1515	
			4,000	12	50	——	——	Cyclic test. Oxide scale observed after 20 cycles. Blade completed 154 cycles. Excessive oxidation at the tip of the blade. Test on this blade terminated.
			11,500	38	30	0.05	1450	
	E3	Formed Timken Alloy 17-22A(S)	11,000	—	30	0.05	1190	
			11,500	—	30	0.05	1515	
			4,000	8	45	——	——	
			11,500	26	15	0.05	1450	Cyclic test. Oxide scale observed after 20 cycles. Blade failed at the base after 106 cycles.
	E4		11,000	—	30	0.05	1190	
			11,500	—	30	0.05	1515	
			4,000	16	40	——	——	Cyclic test. Oxide scale observed after 20 cycles. Blade completed 200 cycles. Test time and conditions considered sufficient to demonstrate the structural durability of this blade. Test on blade terminated.
			11,500	50	—	0.05	1450	

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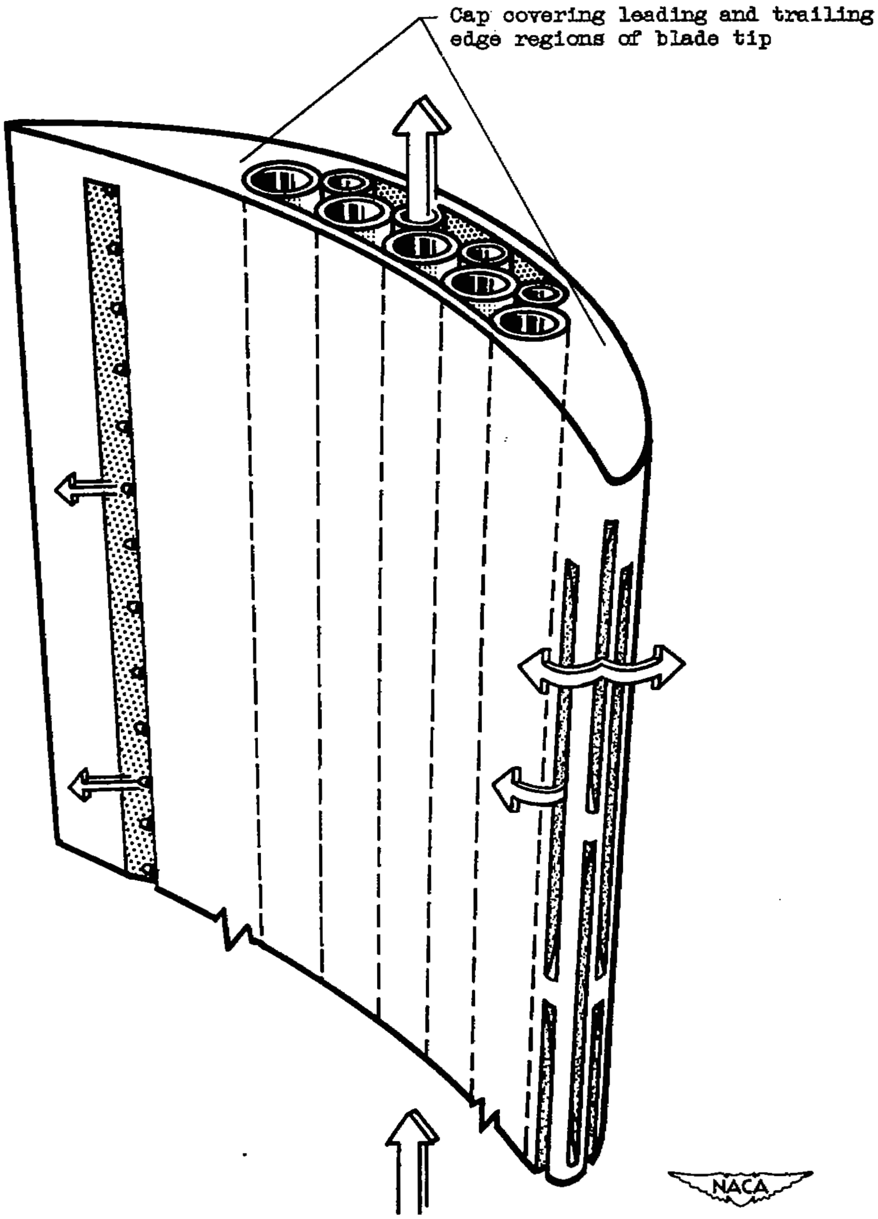

Figure 1. - Air-cooled blade, configuration A. (Arrows indicate cooling-air flow.)

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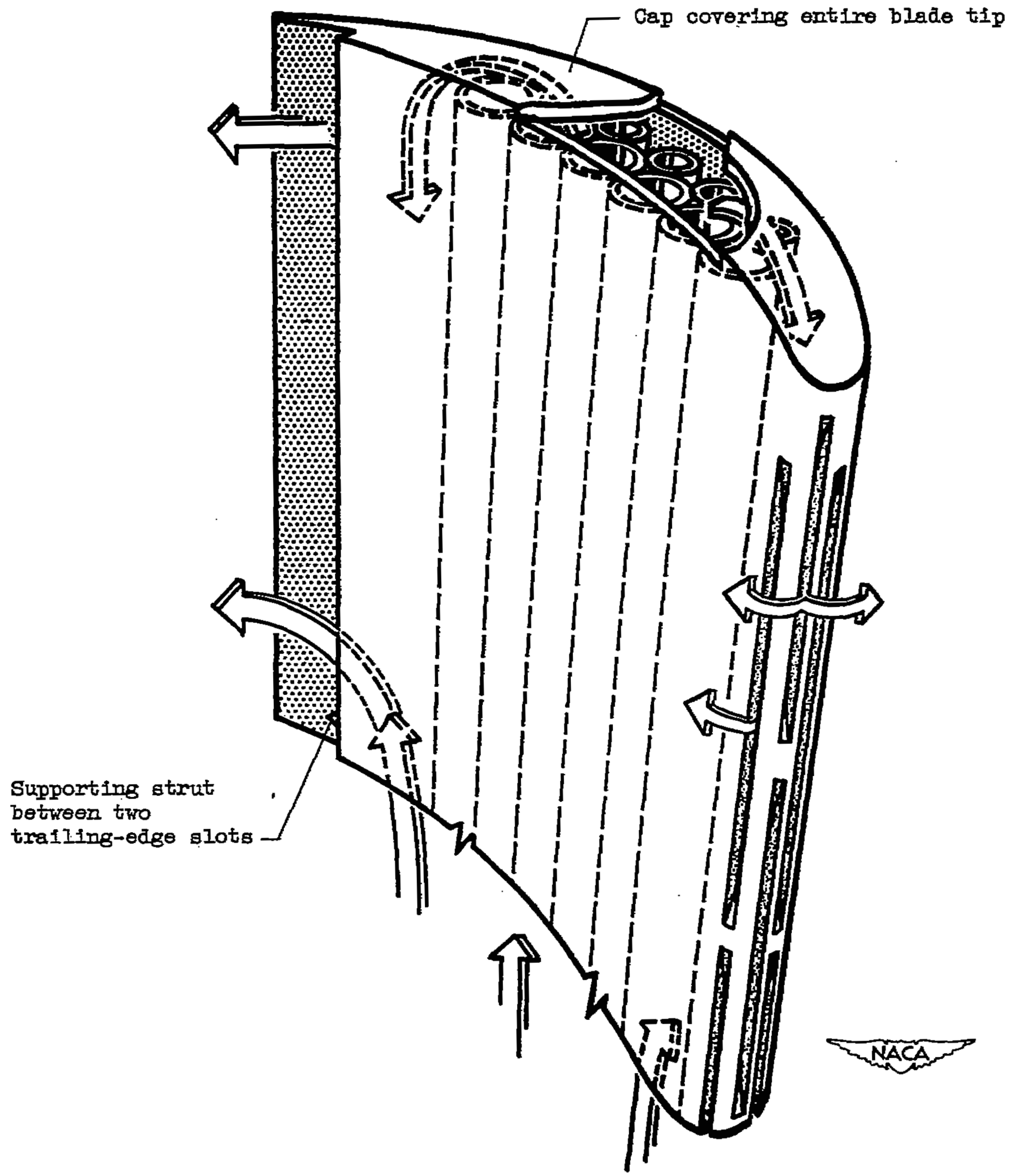

Figure 2. - Air-cooled blade, configuration B. (Arrows indicate cooling-air flow.)

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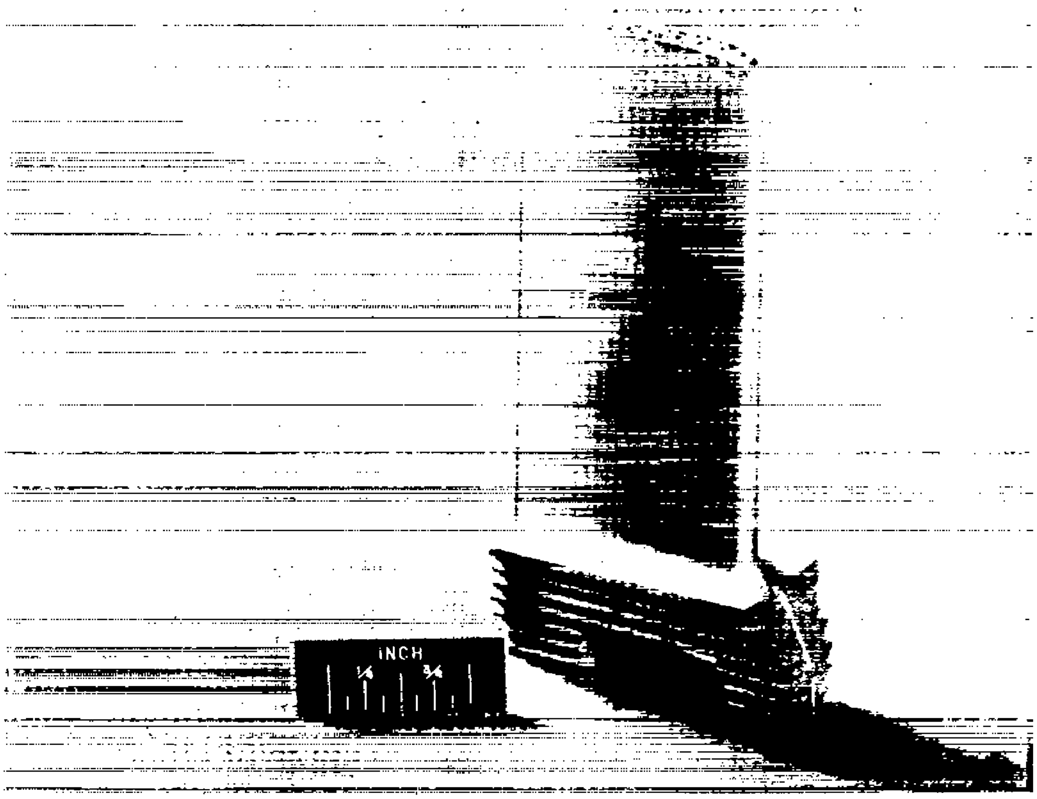
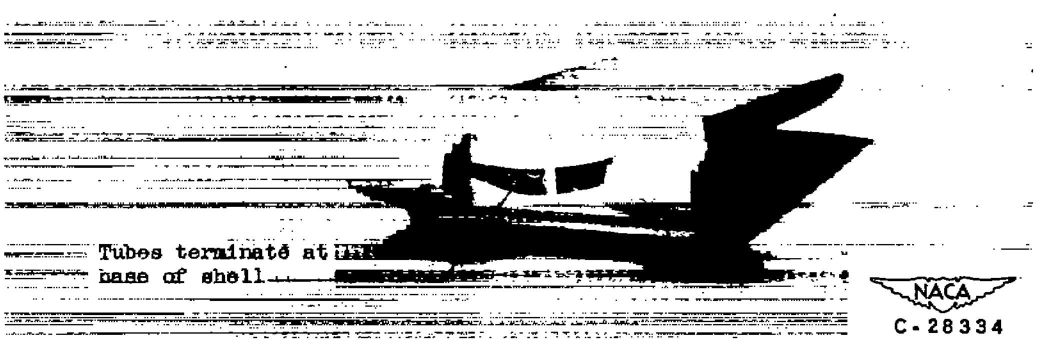


(a) Side view.



(b) Bottom view.

Figure 3. - Air-cooled blade, configuration C.

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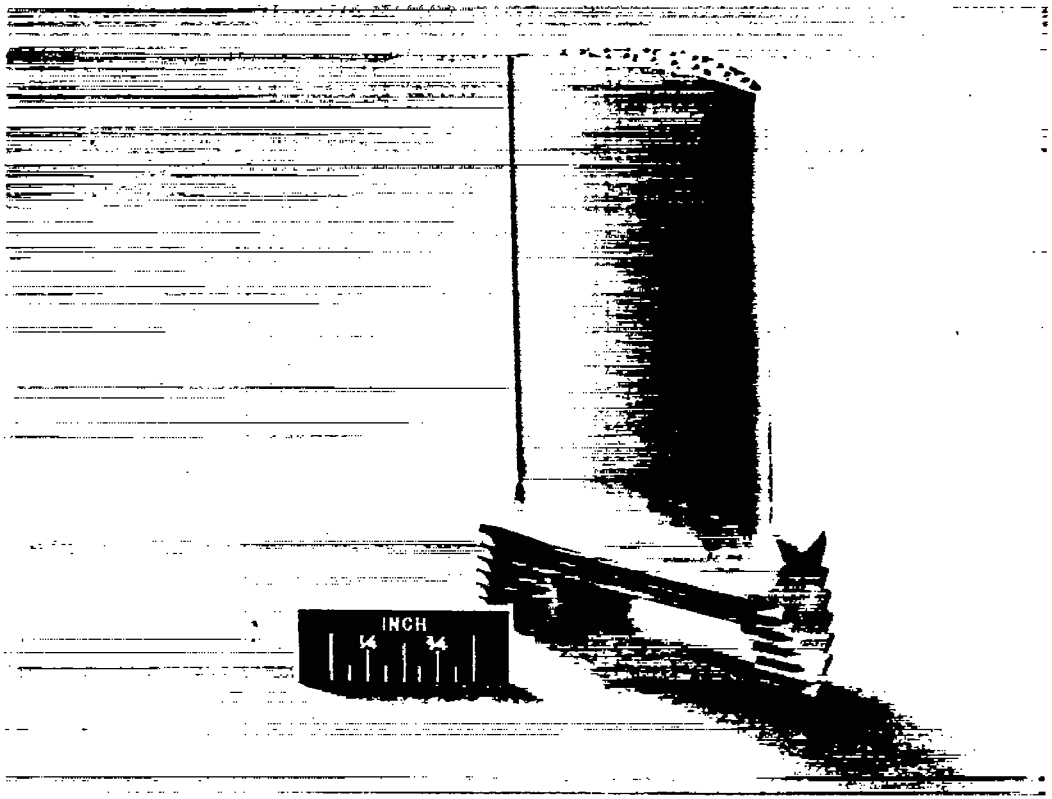
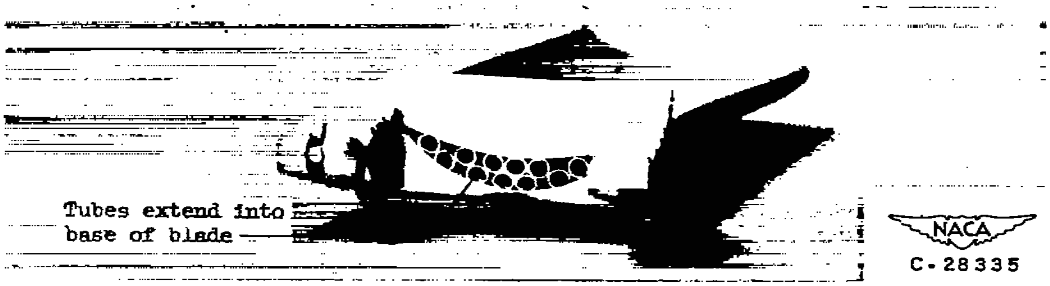


(a) Side view.



(b) Bottom view.

Figure 4. - Air-cooled blade, configuration E.

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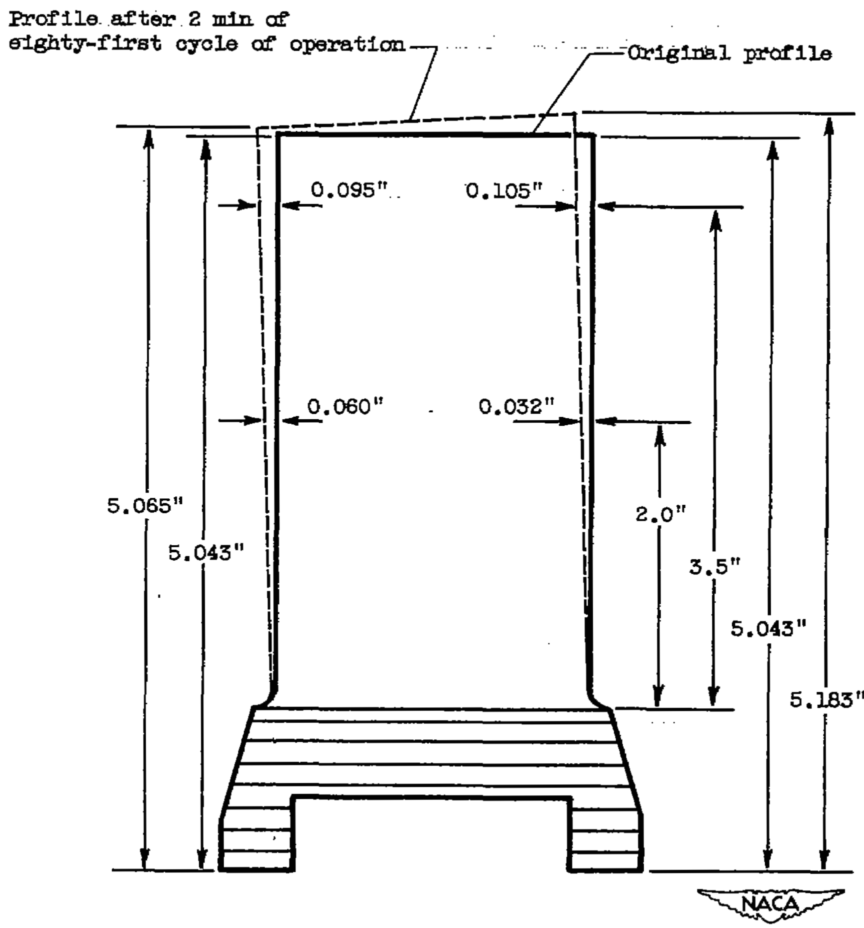

Figure 5. - Distortion and creep of blade C2 (cast of SAE 4130 steel) after 2 minutes of eighty-first cycle of operation.

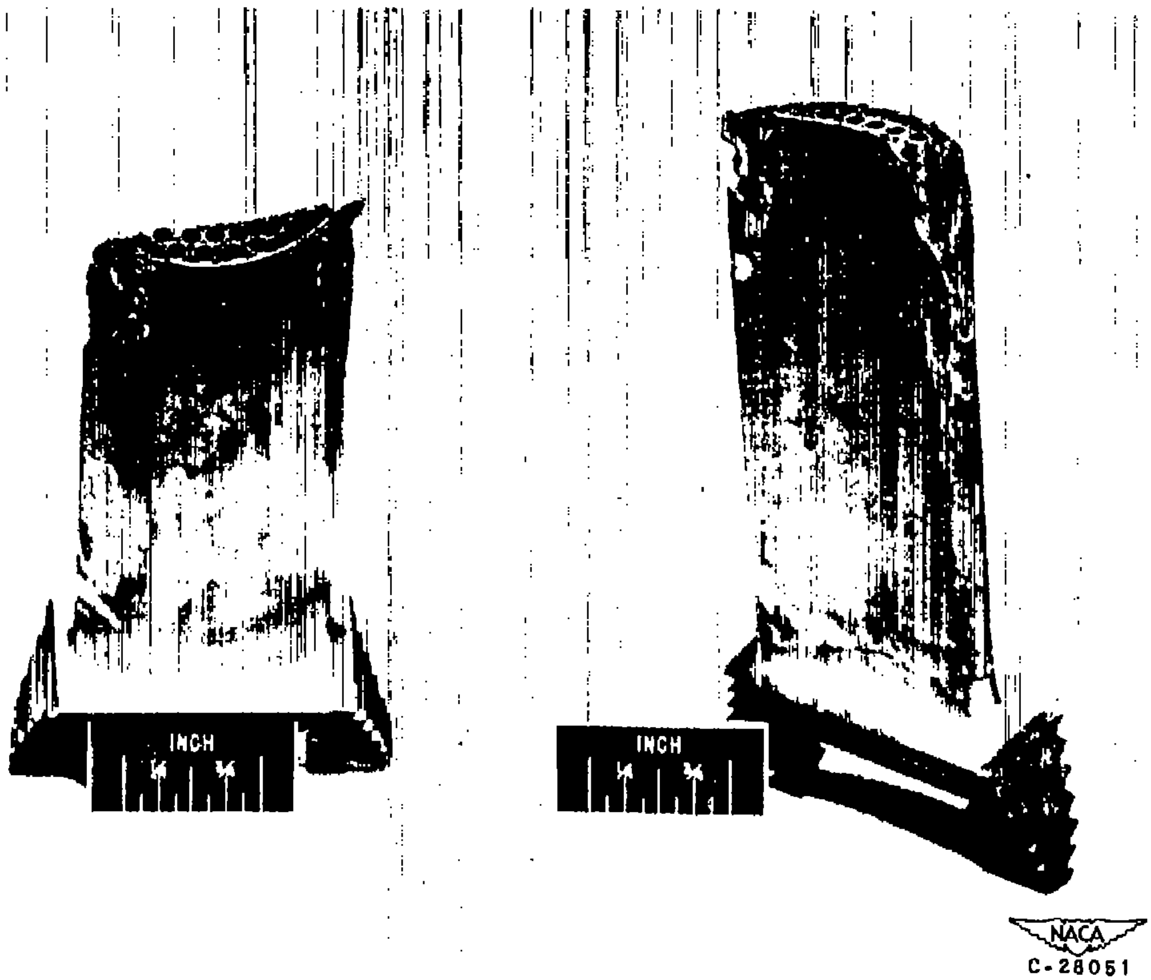

Figure 6. - Condition of blade E2 made of SAE 4130 steel after 154 cycles of operation.

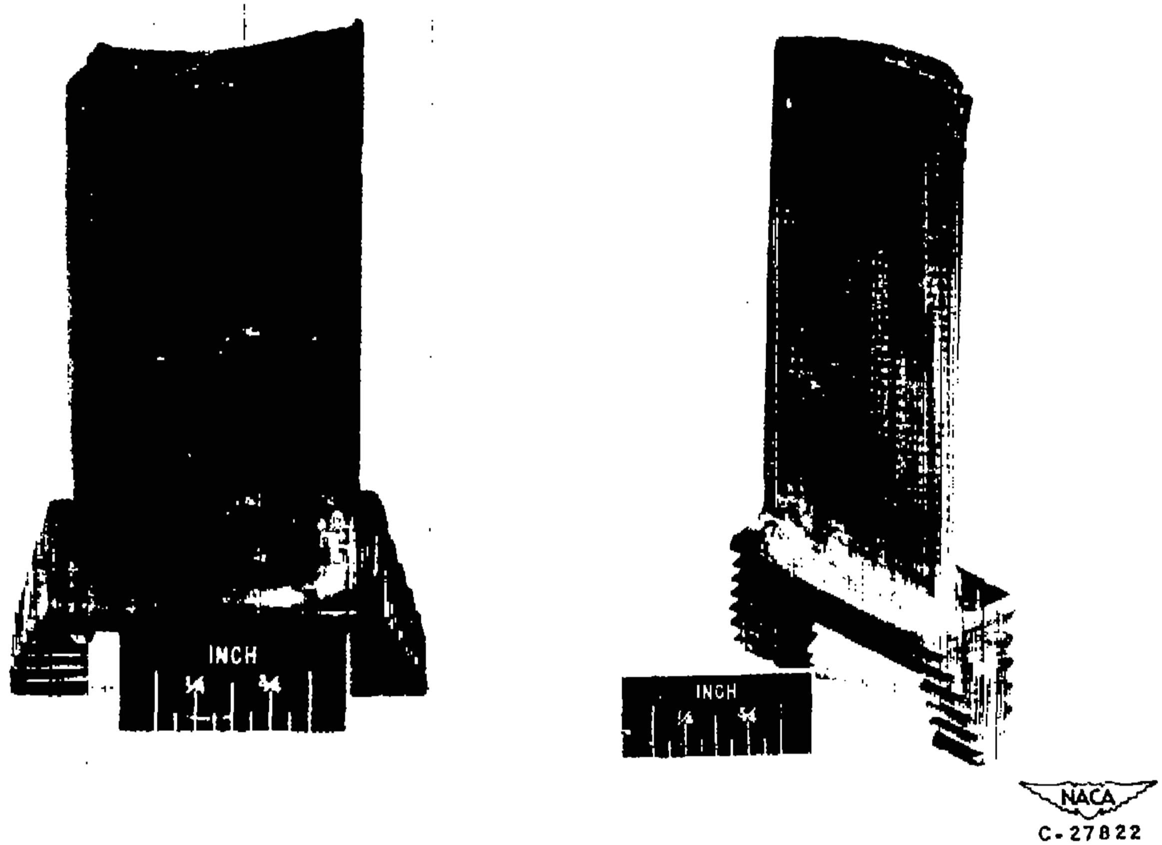

Figure 7. - Condition of blade E4 made of Timken Alloy 17-22A(S) after 200 cycles of operation.

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